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Letters

MODIS Enhanced Vegetation Index data do not show greening of Amazon forests during the 2005 drought

Introduction

In a recent Research review, Asner & Alencar (2010), while discussing Samanta *et al.*'s (2010) report on greenness changes of Amazon forests during the drought of 2005, write 'They found little evidence for green-up during the 2005 drought, and showed that the original work of Saleska *et al.* (2007) was irreproducible' without providing details. The purpose of this letter is to inform the readers of the substantive arguments regarding the irreproducibility of the results of Saleska *et al.* (2007), through providing some new results.

Amazonian forests store some 100 billion tons of carbon in woody biomass (Malhi *et al.*, 2006). Their 'dieback' from reduced precipitation in a progressively warming future climate, as suggested by some studies (e.g. Cox *et al.*, 2004; Salazar *et al.*, 2007; Huntingford *et al.*, 2008), can further accelerate global climate change via carbon release (Cox *et al.*, 2000). In the current climatic regime itself, major droughts – such as those associated with the 1983 and 1998 El Nino events – have served as natural experiments of prolonged moisture stress that enhanced tree mortality and forest flammability (Nepstad *et al.*, 2004, 2007). However, there are conflicting reports of forest response to the more recent drought of 2005, which was different from the previous El Nino southern oscillation

(ENSO)-related droughts in that it intensified during the dry season as opposed to the wet season, and mainly affected southwestern Amazonia but not the central and eastern parts (Marengo *et al.*, 2008). On the one hand, there are reports of higher tree mortality and reduced growth from field studies (Phillips *et al.*, 2009) and enhanced biomass burning (Aragao *et al.*, 2007), while, on the other hand, satellite-based measurements showed extensive forest 'green-up' during this drought (Saleska *et al.*, 2007). Thus, reconciling these opposing reports has been the goal of several studies (Anderson *et al.*, 2010; Samanta *et al.*, 2010).

Saleska *et al.* (2007) reported that Amazon forests had greened-up during the drought of 2005 based on analysis of 2000–2006 July to September (JAS) collection 4 (C4) Enhanced Vegetation Index (EVI) data from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor aboard the NASA Terra satellite. The C4 MODIS data sets were superseded by the current collection 5 (C5) data sets and deleted at NASA data centers. Samanta *et al.* (2010) analyzed both C5 (2000–2008 JAS) and C4 (2000–2005 JAS) EVI data sets – the C4 data were provided by K. Didan, an author listed in Saleska *et al.* (2007), but 2006 JAS data and all C4 pixel level quality flags were missing. All other data used in this research are freely available from the Land Processes Distributed Active Archive Center (https://lpdaac.usgs.gov/).

Irreproducibility

Samanta *et al.* (2010) concluded that the results published in Saleska *et al.* (2007) are not reproducible for the following reasons.

• The greening patterns in Fig. 1(b) of Saleska *et al.* (2007) cannot be reproduced with the current C5 EVI data, irrespective of whether or not the data are screened for cloud and aerosol contamination (Fig. 1c,d in Samanta *et al.* (2010),

respectively). Three prominent patches of greening in Saleska *et al.* (2007), the largest being *c.* 300 000 km², are missing (the circled areas in Fig. 1b of Samanta *et al.*, 2010). The spatial extent of greening decreased by 28–35% and browning increased by approx. 72%, depending on whether or not the corrupted data were filtered (Supporting Information Table S1 in Samanta *et al.*, 2010).

- Similarly, the greening patterns in Saleska *et al.* (2007) cannot be reproduced with the available C4 EVI data if the data are screened for cloud and aerosol contamination using C5 quality flags (Fig. 1a in Samanta *et al.*, 2010). Again, the same three large patches of greening are missing. The greening extent decreased by 36% and browning increased by 65%.
- The greening patterns in Saleska *et al.* (2007), together with the missing patches, can be reproduced if cloud- and aerosol-contaminated EVI data are included in the analysis (Fig. 1b in Samanta *et al.*, 2010). Greening patterns in Saleska *et al.* (2007) can also be reproduced with the available C4 data if cloud-contaminated, but not aerosol-contaminated, EVI data are filtered from the analysis.
- Both C4 and C5 EVI data show nearly identical patterns of greening if the data are screened for cloud and aerosol contamination (Fig. 1a,c in Samanta *et al.*, 2010).

These points suggest that the results of Saleska *et al.* (2007) are not reproducible owing to inclusion of atmosphere-corrupted EVI data, contrary to their claims, either inadvertently or because of faulty C4 quality flags. The quality flags accompanying the $1 \times 1 \text{ km}^2$ C4 EVI data used in these analyses are no longer available. However, C4

and C5 quality flags for a spatially aggregated $0.05^{\circ} \times 0.05^{\circ}$ Terra MODIS EVI data set for the years 2004-2006 are available (Fig. 1) - these data sets were derived from the corresponding 1 × 1 km² data sets used in Saleska et al. (2007) and Samanta et al. (2010). The similarity between C4 and C5 quality flags for cloud corruption (adjacent clouds and mixed clouds) in the drought-affected forest area is 95.6%, 98.6% and 98.5% in 2004, 2005 and 2006, respectively. Likewise, the similarity between C4 and C5 quality flags for aerosol corruption (high aerosol and climatology aerosol) is 78.6%, 87.2% and 88.0% for 2004, 2005 and 2006, respectively. Note that the $0.05^{\circ} \times 0.05^{\circ}$ data are 'cloud-free' composites of the 1 × 1 km² data; therefore, the aggregated quality flags retain aerosol information, which means that the similarity between C4 and C5 flags at $0.05^{\circ} \times 0.05^{\circ}$ will also be true at 1×1 km². These results suggest that aerosol-contaminated, and probably cloudcontaminated, EVI data were inadvertently included by Saleska et al. (2007).

Cloud and aerosol corruption of satellite-based estimates of vegetation greenness is pervasive in the Amazon – even in the dry season, c. 81% of the forest pixels had at least one of the six 16-d EVI composites in the third quarter of 2005 corrupted with clouds or aerosols, and 56% had two or more composites similarly corrupted. Aerosol presence is more extensive during the dry season because of biomass burning (Eck et al., 1998; Koren et al., 2007; Bevan et al., 2009). In the drought-affected region, 82, 58 and 84% of the pixels had aerosol optical thickness (AOT) values of > 0.5 during the last three 16-d compositing periods in the

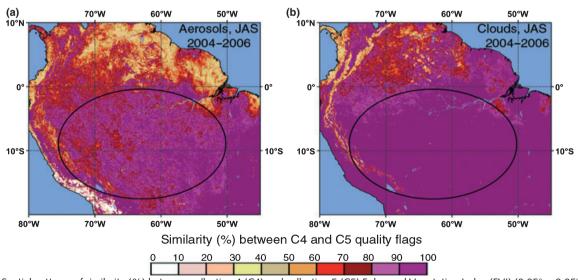


Fig. 1 Spatial patterns of similarity (%) between collection 4 (C4) and collection 5 (C5) Enhanced Vegetation Index (EVI) $(0.05^{\circ} \times 0.05^{\circ})$ quality flags for aerosols (a) and clouds (b) during the July to September (JAS) quarter. A 16-d composite $0.05^{\circ} \times 0.05^{\circ}$ EVI pixel is given a similarity score of 1 when the corresponding C4 and C5 quality flag values are same, which is carried out separately for aerosol and cloud quality flags. Thus, for the JAS quarter during the 2004–2006 time-period, a pixel can have a maximum cumulative similarity score of 18. Then, the similarity (%) of a pixel is calculated as (100 \times (cumulative similarity/maximum cumulative similarity)). The ellipse in the panels shows the 2005 drought-affected region.

third quarter of 2005 – conservatively speaking, over 80% of the drought-affected region was under a thick haze for 40% of the time during the third quarter of 2005. This threshold AOT value of 0.5 at 550 nm is generally taken as the limit beyond which the corresponding surface reflectance data, hence EVI, are deemed not useful for remote sensing of vegetation (Vermote & Kotchenova, 2008).

It is therefore instructive to examine how atmospheric corruption impacted C4 and C5 EVI data. We used C5 quality flags to identify corrupted and uncorrupted pixels for both C4 and C5 EVI data. This allowed an accurate assessment of the atmosphere corruption effects on EVI across Collections by not introducing errors related to changes in data filters between Collections. The difference in uncorrupted EVI values between C4 and C5 is, as to be expected, negligible (0.02 or less compared with an average EVI value of 0.5), both during the dry season of 2005 and also in other years. Interestingly, the difference between corrupted and uncorrupted C5 EVI values is small, which must be a result of refinements to atmospheric correction (Vermote & Kotchenova, 2008) and EVI algorithms (Didan & Huete, 2006), because the difference between these two classes of pixels in C4 is quite large - corrupted EVI values are greater than uncorrupted values by 0.1 and more, especially in areas of high amounts of aerosol. Aside from the large difference, the sign of this change is counter intuitive, because atmospheric corruption will decrease vegetation greenness values - for example, Normalized Difference Vegetation Index (NDVI) decreases as a result of such corruption (Holben, 1986). The large positive difference suggests incomplete atmospheric correction, resulting in incorrectly large near-infrared reflectances and/or incorrect blue to red reflectance ratios, both of which can result in spuriously high EVI values given its formulation. This error is further compounded by the maximum-value compositing routine in the EVI algorithm, that is, the algorithm finally outputs the largest of this set of artificially inflated EVI values. This explains the spurious greening in Saleska et al. (2007) and why it is not reproducible.

Spatial extent of greening

A topic of contention has been the spatial extent of greening. Of the nearly 2.19 million km² of intact Amazon forests in the drought-stricken region, 12% (0.26 million km²) show anomalous greening (EVI standardized anomalies > +1), 6% (0.13 million km²) show browning (EVI standardized anomalies < -1) and 22% (0.48 million km²) show no EVI changes (EVI standardized anomalies between -1 and +1) – the rest, 60% (1.32 million km²), have atmosphere-corrupted EVI data, and are therefore excluded from further analysis (Samanta *et al.*, 2010). It is prudent to explore whether the area with uncorrupted EVI data (40%) is representative of the entire drought-affected region. If so, the

EVI dynamics may be expressed relative to the area of valid data, in which case the greening and browning proportions increase to 30% and 15%, respectively. The dominant pattern still remains one of no greenness changes (55%), and, together with browning, represents an overwhelmingly nongreening response of these forests to the 2005 drought (70%). We show later that the area sampled is not representative of the larger drought-affected region, that is, the sample of pixels with uncorrupted EVI data is not representative of the total population of pixels in the drought region, and therefore any arguments regarding expressing greening and browning proportions with respect to smaller area and using uncorrupted data are without merit.

Atmosphere corruption of EVI data owing to clouds and aerosols is highly selective, both spatially and temporally. The broad precipitation gradient in the Amazon, and its seasonal variation, from the less humid southeast to the more humid northwest (Sombroek, 2001) implies a similar gradient in cloud persistence - therefore, the probability of obtaining cloud-free satellite data in the more humid forests is selectively lower. Aerosols from biomass burning are predominant in the southeastern fringes in the dry season – for example, Fig. 3 in Aragao et al. (2007) - therefore, the probability of EVI corruption from aerosols is selectively higher in these areas during the dry season and nearly nonexistent in other seasons (April to June, for example). Thus, forests to the northwest and southeast will be undersampled and forests to the center will be over-sampled – a fact underscored by the analysis of 7 yr of EVI data (Fig. 2; similar patterns for other quarters are not shown for brevity). Given the rich diversity of species and their varied responses to variations in climate, this biased sampling argues against extrapolating the uncorrupted data available for the smaller area to the much larger drought-affected region.

The area with uncorrupted EVI data increases to 65–75% of the drought-affected region if the analysis is performed on monthly, rather than quarterly, standardized anomalies. However, a predominant proportion (60–65%) still shows no anomalous EVI changes in each of the 3 months of the dry season, consistent with the analysis on quarterly standardized anomalies.

In fact, the use of a threshold value of standardized anomaly (± 1 SD) alone to categorize greenness dynamics, as in Saleska *et al.* (2007), without an account of the magnitude (absolute value) of EVI changes, relative to EVI accuracy, is misleading, for it does not indicate whether or not the observed anomalies are real. For instance, the 60% of all EVI anomalies that are within 0.02 EVI in magnitude may be considered insignificant, because the 1 SD envelope of error in EVI is ± (0.02 + 2% of EVI) (Vermote & Kotchenova, 2008). Similarly, 97% of the EVI anomalies in greening and 94% in browning categories fall within the 2 SD (95% confidence interval) envelope of error in EVI (± 0.06, which is *c.* 12% of the climatological dry season

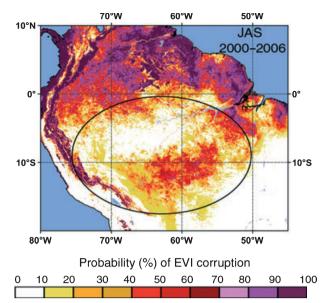


Fig. 2 Spatial patterns of the probability (%) of Enhanced Vegetation Index (EVI) $(1 \times 1 \text{ km}^2)$ corruption during the July to September (JAS) quarter. A 16-d composite collection 5 (C5) EVI value is valid when its quality flags indicate absence of clouds (adjacent clouds, mixed clouds and possible shadows) and aerosols (climatology and high). If at least one 16-d composite is valid in a month, then the monthly EVI is valid. Similarly, if all 3 months in a quarter have a valid EVI, then the quarterly EVI is valid and the $1 \times 1 \text{ km}^2$ pixel is given a validity score of 1. Thus, for each quarter during the 2000–2006 time-period, a pixel can have a maximum cumulative validity score of 7. Then, the probability (%) of validity of a pixel is calculated as $(100 \times (\text{cumulative validity/maximum})$ cumulative validity)). Finally, the probability (%) of corruption of the pixel is calculated as (100-probability) of validity). The ellipse in the figure shows the 2005 drought-affected region.

average EVI value of 0.51). Thus, using a threshold of 12% EVI change, in addition to 1 SD, to categorize EVI dynamics, reduces the anomalous greening and browning proportions to 0.6% and 0.5%, respectively. This further reinforces the dominant greenness dynamic as one of no changes during the dry-season drought of 2005. The fact that a majority of the measured EVI anomalies are insignificantly small could suggest either reflectance saturation in dense Amazon canopies or no real changes in the greenness of these forests.

It is also of interest to contrast the greenness dynamics of forests within the drought-affected region to forests outside this region, but in the general vicinity, for example, south of the equator. Of the nearly 2.44 million km² of such forests, *c.* 5% (0.12 million km²) show anomalous greening, 5% (0.12 million km²) show browning and 14% (0.34 million km²) show no EVI changes – the rest, 76% (1.86 million km²), have atmosphere-corrupted data and are therefore excluded from analysis. Nearly 93% of these forests with uncorrupted data have EVI anomalies that fall within the 2 SD (95% confidence interval) envelope of error in EVI. Thus, as before, using a threshold of 12% EVI change, in addition to 1 SD, to categorize greenness dynam-

ics, reduces the fractions of greening and browning to 0.5% and 1.7%, respectively. Therefore, as with forests in the drought-affected region, the dominant greenness dynamic in forests outside is also one of no EVI changes.

Concluding remarks

The argumentation and results discussed earlier reinforce the conclusions in Samanta et al. (2010), namely, the results of Saleska et al. (2007) are not reproducible owing to inclusion of atmosphere-corrupted data in their analysis and there was no large-scale greening of Amazon forests during the 2005 drought. The speculation in Saleska et al. (2007), that increased sunlight levels during the drought might have somehow caused the forests to green-up, is also refuted through analysis of solar irradiance data in Samanta et al. (2010). Small random patches of anomalous greening and browning appear in all 9 yr (2000-2008), irrespective of contemporaneous variations in precipitation and with no persistence over time. The fact that > 90% of the EVI anomalies are insignificantly small – within a 2 SD (95% confidence interval) envelope of error in EVI – and the lack of correlation between the magnitude of EVI anomalies and severity of drought, further supports the conclusions of Samanta et al. (2010). Finally, we note that the MODIS data are not 'coarse-resolution observations' as Asner & Alencar (2010) state, but are of moderate resolution - the EVI data are available at 250 m resolution, but both Saleska et al. (2007) and Samanta et al. (2010) used 1 km EVI data in their analyses.

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